The Thesis Committee for Olivia Hanjani Loa
Certifies that this is the approved version of the following thesis:

Economic Analysis of Wind Power Integration in the Eastern Sumba Grid, Indonesia

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor:

____
Fred C. Beach

____
James R. Kyle

____
Warren J. Hahn

Economic Analysis of Wind Power Integration in the Eastern Sumba Grid, Indonesia

by

Olivia Hanjani Loa

Thesis

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Dedication

Papa and Mama, whose continued outpour of love and support inspire me to be the best in all I do;

Koko, who introduced me to the energy industry through the nature of sibling rivalry,

This thesis is for you.

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Abstract

Economic Analysis of Wind Power Integration in the Eastern Sumba Grid, Indonesia

Olivia Hanjani Loa, M.S. E.E.R.

The University of Texas at Austin, 2018

Supervisor: Fred C. Beach

The island of Sumba serves as an example of a physically isolated electricity market that continues to burn diesel fuel to generate electricity despite possessing abundant sources of wind power. In an effort to encourage wind power use in Eastern Sumba, NREL has recently conducted a study evaluating the technical feasibility of integrating wind power into the Eastern Sumba grid. A cost-benefit analysis with three economic indicators has been performed for measuring the economic feasibility of integrating an 850-kW wind power system in the Eastern Sumba grid. The results demonstrated that the wind power system carries a much lower generation cost and subsidy rate than the diesel generator with a payback period of 2.9 years. Three cost-reduction scenarios were proposed to bring the generation cost to a breakeven point with the current electricity price. While a breakeven point could not be reached, the combination of CRF and CAPEX reduction scenario has successfully reduced the wind power system generation cost by 35% and cut the current energy subsidy by 94%. This study is hoped to encourage more rigorous renewable energy deployment in Eastern Sumba and to catalyze the process of reaching 100% electrification rate in the Sumba island with renewable energy power generation.

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Chapter 1

Introduction

1.1 Background

Energy poverty is defined as the lack of access to modern energy resources, such as electricity and transportation fuel, to support basic human needs. This has become a devastating problem in the developing countries because energy access has a significant correlation to the socio-economic development of a nation (Castlerock Consulting, 2015). Nearly 17% of the global population does not have access to electricity, and 95% of these people live in developing countries across Asia and Africa (EIA, 2018). Developing countries increasingly turn to renewable energy sources as a solution to energy poverty as these countries typically are vulnerable to climate change. Furthermore, robust technology development in recent years has competitively dropped the renewable energy cost. The culmination of population and economic growth across developing countries will surely drive those nations to become emerging leaders in the renewable energy market (Bloomberg New Energy Finance, 2017).

Isolated islands in the developing countries suffer the most from energy poverty. These islands lack properly-run energy infrastructures, and do not have the option to be interconnected to the larger grid in the mainland. Coupled with an urgency to increase electricity access and to improve local productivity and economy, isolated islands have become an appealing option as pilot test grounds for breakthrough renewable energy innovations (Notton, 2015).

Sumba island is one of the leading examples of the energy transformation happening in isolated islands. More than 80% of the electricity on the island is generated by diesel fuel. However, the distribution and transportation of fuel from the main islands of Java and Sumatra is very costly, and thus translate into excessively high fuel prices in the Sumba island region. With low purchasing power in Sumba, many inhabitants are unable to afford electricity costs even with fuel and electricity subsidies offered by the government, and so resort to living without power. Energy access ties strongly with economic productivity, thus it is not surprising that Sumba, an island where only one-fourth of the population has access to electricity in 2010, ranked as one of the poorest regions in Indonesia (van der Veen, 2011). Fortunately, Sumba island has abundant renewable energy resources (e.g. solar, wind, hydro, biomass) that could be developed as a prominent solution for energy poverty. It is, therefore, a priority for the government to harness the renewable energy potential for electricity generation in Sumba.

Hivos International, a non-profit organization supporting sustainable energy development, introduced Sumba Iconic Island (SII) as an initiative to promote 100% renewable energy use in Sumba. This program was positively received by the Indonesian government and was validated by the Ministry of Energy and Mineral Resources through the Ministerial Decree No. 3051. The decree manifested a goal to achieve a 100% electrification rate (ratio of people with electricity access to the total population) in Sumba by 2020 with 95% of the electricity generation generated from renewable energy sources (Ministerial Decree No. 3051 K/30/MEM/2015). The program received attention and support from international agencies, such as the Danish International Development Agency

(DANIDA) and the Asian Development Bank (ADB). The Sumba Iconic Island program is expected to pave the path for other isolated islands in developing countries to pursue similar energy plans as a solution to stimulate socio-economic development, prioritizing renewable energy resources as an alternative to conventional fuel.

Figure 1. Electricity grid connection in Sumba island, with Eastern Sumba occupies more than half of the island land area.

Eastern Sumba is chosen for the scope of this thesis as it is the largest administrative district in Sumba and possesses the highest wind power potential on the island. Regardless, the Eastern Sumba grid still currently relies completely on subsidized diesel fuel to generate electricity. Fuel, including gasoline and diesel, is highly subsidized by the Indonesian government due to the volatility of the fuel market, which is sensitive to national economic stability.

There are three main purposes of replacing diesel fuel with wind power in electricity generation: (1) to liberate the Eastern Sumba population from energy poverty by providing reliable energy resources, (2) to lower government spending on fuel and electricity subsidies, and (3) to create a compelling case for the private sector and foreign investors to invest more in renewable energy projects. A solution to integrate renewable energy into the Eastern Sumba grid was proposed in the National Renewable Energy Laboratory (NREL) report "System Impact Study of the Eastern Grid of Sumba Island, Indonesia", which was just published in 2016. The proposed solution was to create a renewable energy system comprising of the available energy resources (solar/wind), hybrid controller, energy storage, and diesel generators. The system aims to deliver sustainable power production into the Eastern Sumba grid while replacing the existing diesel generators. While the technical feasibility of the renewable energy system has been verified by the NREL team, the other sectors, including the economic, environmental, and policy impacts, need to be assessed further.

Therefore, this thesis will focus on the economic analysis of the integration of wind power system into the grid by performing a cost-benefit analysis of the power system using the levelized cost of energy (LCOE), the subsidy rate, and the payback period as the main parameters. LCOE sensitivity is also evaluated to determine potential LCOE reduction based on the main cost drivers influencing the LCOE value. This study will provide some insights into the cost-competitiveness of wind power systems that are hoped to no only encourage more rigorous renewable energy deployment in Eastern Sumba and eventually the entire Sumba island community, but also to hasten the process of reaching 100% electrification rate in Sumba.

1.2. OBJECTIVES

This thesis has three main objectives:

1. Perform a cost-benefit analysis and determine the economic feasibility of replacing diesel generation with wind power in Eastern Sumba
2. Identify the main driver of the LCOE value in the wind power system
3. Propose LCOE reduction scenarios to make the wind power system a more affordable to implement and profitable in the long run.

1.3 METHODOLOGY

To achieve such objectives, an economic analysis will be conducted based on the technical feasibility of the wind power project with detailed approaches as follows:

1. Observe the energy profile and supply/demand trends in Eastern Sumba island.
2. Evaluate wind potential in Sumba and estimate the projected wind power generation using NREL's wind power system.
3. Perform a levelized cost of energy (LCOE) analysis by incorporating annual CAPEX, OPEX, and net annual energy production discounted to the present value. Estimate subsidy rate and payback period based on the LCOE value with respect to the current electricity rate.

4. Compare the LCOE, subsidy rate, and payback period of the wind power system to ones from the existing diesel generator system
5. Run sensitivity and regression analyses using the Monte Carlo simulation to determine the main LCOE drivers from the LCOE components.
6. Generate LCOE reduction scenarios to determine the most cost-effective way to reduce LCOE and make necessary reductions/ shifts in subsidy value.

1.4 Thesis Structure

This thesis consists of six chapters. Chapter 1 introduces the objective and scope of the thesis project. Chapter 2 is an overview of Eastern Sumba's demographic and its current energy profile. Chapter 3 overlays the cumulative wind power potential in Eastern Sumba, along with the proposed wind turbine generation system and the estimated annual energy production. Chapter 4 estimates project's economic feasibility by comparing calculated wind power LCOE to the diesel power LCOE and to the current electricity price. Chapter 5 provides in-depth sensitivity and regression analyses to identify possible LCOE reductions by changing LCOE component values. Chapter 6 summarizes findings and suggests recommendations in furthering this thesis project to benefit all parties involved in developing better energy infrastructure in the Eastern Sumba district.

Chapter 2

Eastern Sumba Demographics and Energy Supply/Demand Analysis

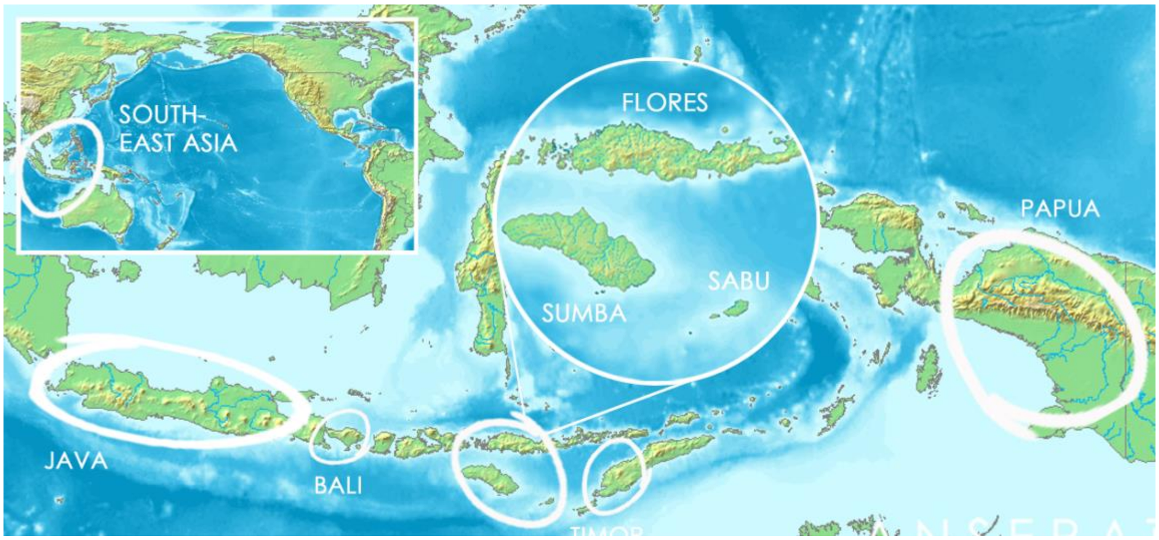

Figure 2. Illustration of the Sumba Island geographical location (Anserai, 2016)

2.1. EASTERN SUMBA DEMOGRAPHICS

Eastern Sumba is the largest administrative district in Sumba island, an isolated island located in the Southeast of the Indonesian archipelago. The island is adjacent to Sumbawa Island to the Northwest, West Timor Island to the East, and Australia to the far South. Eastern Sumba consists of 249,606 inhabitants, making up 32% of the total Sumba island population (Badan Pusat Statistik, 2017). Table 1 summarizes Eastern Sumba's demographics, which includes socio-economic indicators such as poverty rate (ratio of population whose income falls below 50% of average median income) and GDP per capita. A wide economic disparity exists between the Eastern Sumba region and the rest of the country – the GDP per capita in Eastern Sumba is only one third of the national average.

Moreover, the poverty rate in Eastern Sumba is 31%, which is three times higher than the national rate. The main reason for the region's low economic performance and prevalent poverty is the lack of access to electricity. Only 48% of the Eastern Sumba population has access to electricity for residential and commercial purposes, including education and healthcare (Castlerock Consulting, 2015). Others are forced to live in the darkness, utilizing low-grade energy resources, such as wood and kerosene, to support their energy needs.

Demographics	**Eastern Sumba**	**Sumba Island**	**Indonesia**
Area (km^2)	7,000	11,060	1,904,569
Population	249,606	768,824	261,115,456
Poverty Rate (%)	31.43	31.99	10.64
GDP per capita (USD)*	$1,326.68	$927.40	$3,336.10

**) for reference, the current world and US GDP are $10,161.60 and $56,469.00 respectively (World Bank, 2017)*

Table 1. Sumba geographic, demographic, and economic indicators (Badan Pusat Statistik, 2017)

Agriculture and commerce sectors make up the largest sectors of Eastern Sumba's economy (Badan Pusat Statistik, 2017). The agriculture sector includes farming, forestry, and fishery, while the commerce sector ranges from home-industry (local handicraft) to tourism. Because of the arid soil and mountainous terrain of the Eastern Sumba landscape, the agricultural production is limited and difficult to expand. On the other hand, the commerce sector has seen rapid expansion. Tourism especially has benefitted from the vigorous efforts of the government and private sector to develop eco-tourism in the region, promoting the exotic sceneries still in pristine condition. Sustainable tourism requires access to energy, another reason supporting the development of renewable energy infrastructures. As an economic segment, energy remains underdeveloped. Developing renewable energy infrastructures would create job opportunities, improving the energy sector's contribution to the regional income and encouraging a robust economic growth in the region.

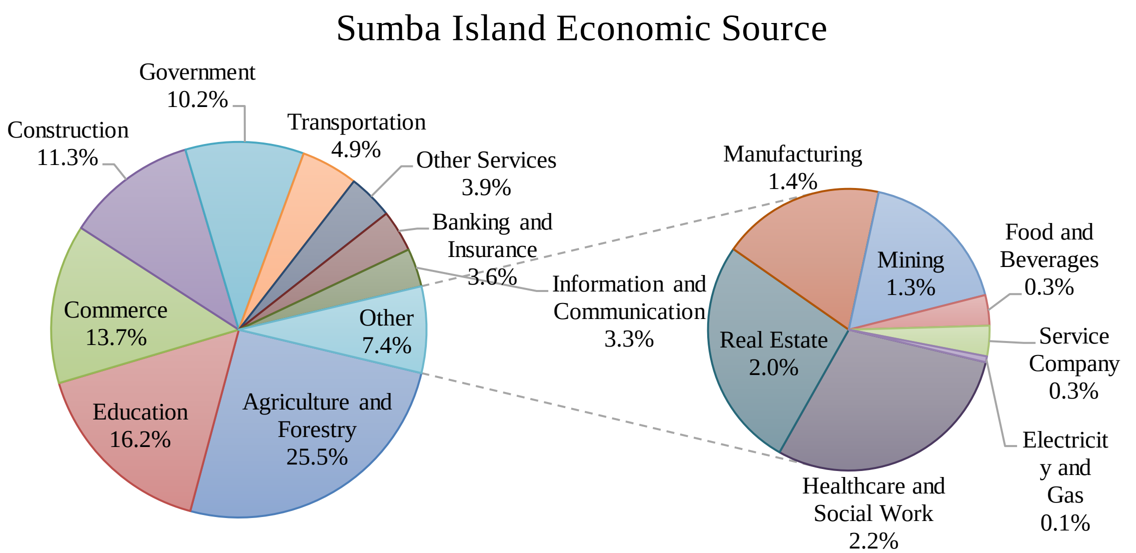

Figure 3. Economic sectors in Eastern Sumba based on the regional gross domestic product in 2016 (Badan Pusat Statistik, 2017)

2.2. EASTERN SUMBA ENERGY PROFILE

Power production and distribution, including grid connection and power system operation, are fully managed by the national utility company, Perusahaan Listrik Nasional (PLN). Two diesel-based power systems consisting of 16 diesel generators, with capacities ranging from 220kW to 650 kW, currently deliver power to the Waingapu grid – the only grid existing in Eastern Sumba. Energy demand is measured based on the peak load in the Waingapu grid system, with the peak load of 5.682 MW around 6.00 PM and a minimum load of 2.75 MW during daytime (Hirsch et al., 2015). The electricity produced in this grid is approximately 33,000,000 kWh, which only covers 48% the real total energy demand in the Eastern Sumba region. This value is estimated to grow significantly in the next decade with the government's attempt to improve electricity access in the region, not to mention the rapid annual population growth of 1.3% (Badan Pusat Statistik, 2017).

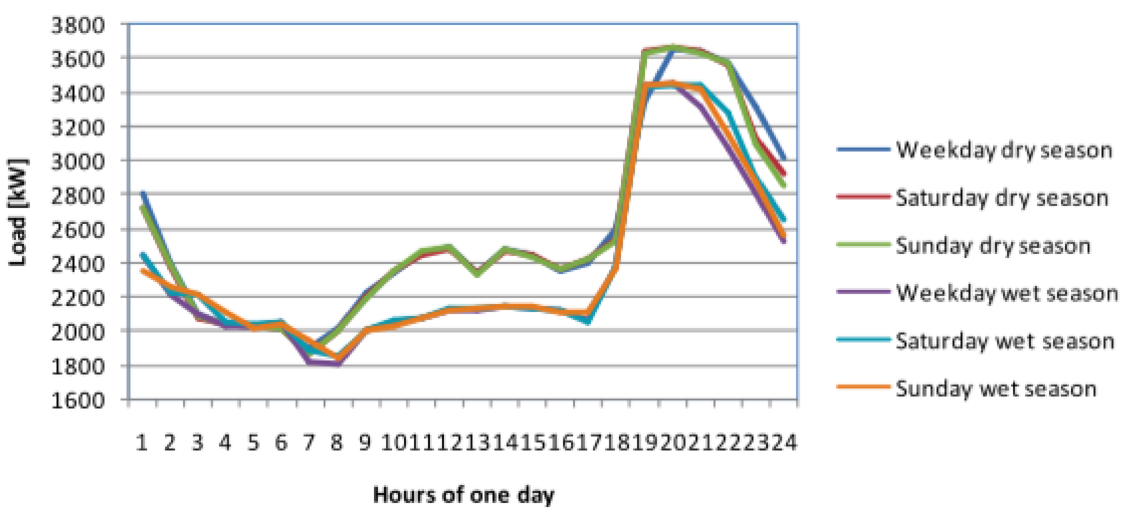

Figure 4. The average daily load in Waingapu grid (Oswal et al., 2016)

Power Plant	Type	Power (kW)	Peak Load (kW)	
			Day	Night
Waingapu	DRO 216	220	0	0
	6ML-HTS	220	0	195
	BA 6 M 816 U	180	0	150
	BA 6 M 816 U	180	0	0
	DRO 216	220	0	180
	DRO 217	200	0	180
	CAT 32	550	0	530
Kambajawa	TAD 1630 GE	220	0	215
	18V2000G62	650	515	630
	D2842LE201	430	0	430
Rental	12V1600 G20F	430	280	280
	12V1600 G20F	430	375	405
	12V1600 G20F	430	395	405
	12V1600 G20F	430	380	380
	12V1600 G20F	430	400	410
	12V1600 G20F	430	400	410

Table 2. Current diesel power generation in Eastern Sumba district (Castlerock Consulting, 2015)

Eastern Sumba's present diesel power energy generation system faces two main challenges: the lack of diesel fuel availability and high costs of power generation resulting in a need for government subsidies. Diesel fuel distribution and transportation costs are inflated as supply is currently being sourced from the main islands. Moreover, the amount of diesel fuel transported to the island is often disrupted by the weather. Limited fuel availability on the island compounded with high prices, and the failure to anticipate a sudden increase in peak load - all result in frequent outages in the Eastern Sumba district (Winrock International, 2010). Fuel and electricity costs are heavily subsidized nationwide by the Indonesian government to ensure that citizens are able to afford these resources, protecting citizens against oil and gas market volatility (Eller and Gauntlett, 2015). In 2013, electricity subsidies reached peak values of $10 billion USD for electricity and $17 billion USD for fuel. Since 2014, the government has significantly reduced fuel and electricity subsidies in an attempt to encourage more renewable energy utilization; yet, annual subsidy values remain at $1.5 billion USD for electricity and $ 500 million USD for diesel and gasoline (Lontoh et al., 2015; Wulandari et. al., 2014).

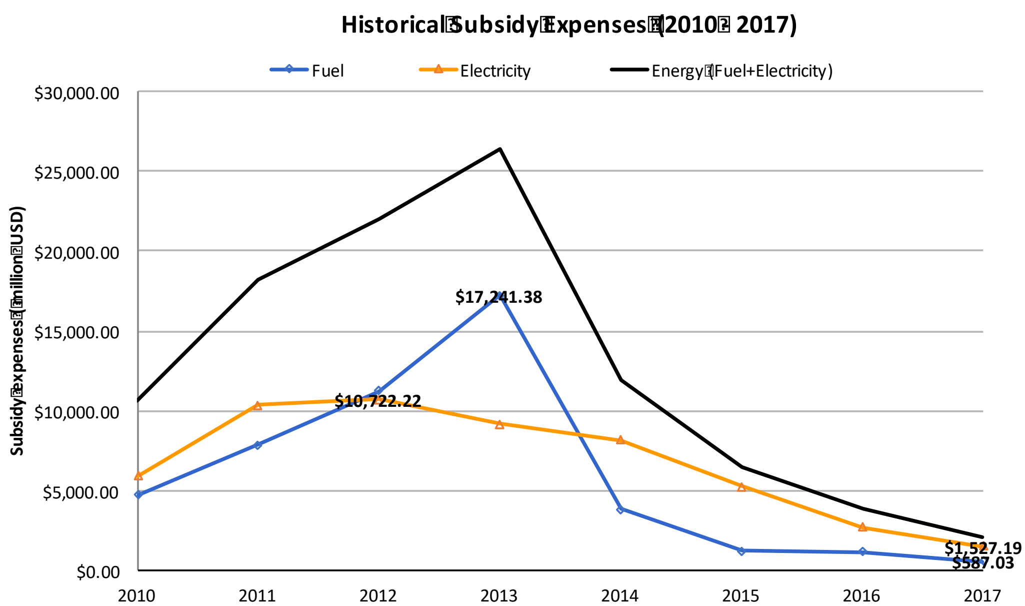

Figure 5. Historical trend of fuel and electricity subsidies for electricity generation in Indonesia (BPH Migas, 2017; Ihsanuddin, 2017)

In Eastern Sumba, these subsidies are applied to the operational cost of the power generation, with the main component being costs of diesel fuel. However, electricity generation remains costly as the fuel subsidy does not account for the transportation and distribution costs in bringing the diesel fuel to the island (Dabu, 2012). As the government strives to reduce fuel subsidies, an increase in operational cost is expected, which then translates into greater power generation costs. In order to maintain the present electricity retail price, the government must instill greater electricity subsidies in anticipation of the rise in power generation costs. Replacing diesel generation with renewable energy power systems will decrease fuel consumption, thus eliminate the need for a fuel subsidy and in turn avoiding unnecessary increases in electricity subsidies.

The island boasts availability of different types of renewable energy resources, such as solar, wind, hydro and biomass, all of which have potential to replace the diesel power generation system. Especially in Eastern Sumba, the combination of mountainous landscape and arid areas are advantageous for wind power generation (Castlerock Consulting, 2015). Nonetheless, the high upfront costs of wind power remain a significant problem that discourages PLN from investing in a utility-scale wind power system. Furthermore, private sector, including non-government organizations and energy companies, have little incentives to invest in renewable energy projects because Power Purchase Agreements (PPA) are often associated with unattractive rates of return (Winrock International, 2010). This issue may be addressed by reducing current fuel and electricity subsidies and investing those subsidies instead in renewable energy incentives. Importantly, incentives are only necessary during the first few years of renewable power system operations. Operating costs do not require subsidizing because the resources naturally exist and is free to be harvested. Hence, subsidy rates are reduced in the long run, and external parties are encouraged to be more involved in a robust deployment of renewable energy in Eastern Sumba.

Chapter 3

Wind Power Assessment in Eastern Sumba

3.1. EASTERN SUMBA WIND POTENTIAL

Eastern Sumba has the most wind power potential amongst other districts in the Sumba island. The mountainous contour creates high wind speeds that are both accessible and sufficient for power generation. Large arid areas in Eastern Sumba district, though unusable for agriculture purposes, are suitable for building energy infrastructure, such as wind power system. In addition, the long dry season, influenced by the North Australian dry climate, will ensure constant energy production and thus grid reliability, as wind speeds are consistent throughout the year (Jain, 2015).

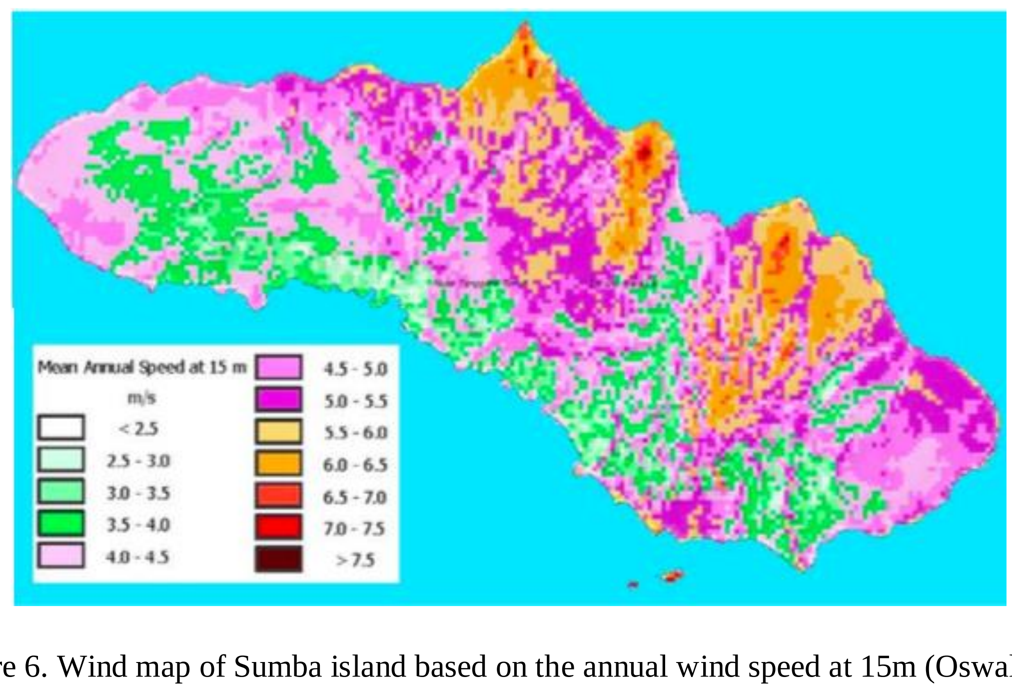

Figure 6. Wind map of Sumba island based on the annual wind speed at 15m (Oswal et al., 2016).

Winrock consulting performed a preliminary site assessment with hopes of determining the most feasible location for wind power generation in Eastern Sumba. Various locations were assessed based on optimum wind power harvested and vicinity to the nearby grid. Two wind sites, Hambapraing and were selected for their locations are adjacent to the medium voltage grid connection, albeit not having the highest theoretical wind speed (Winrock International, 2010). Moreover, the fact that these sites are located in the coastal area creates opportunities for expanding the wind power system offshore should greater energy production be necessary to fulfill growing energy demand.

Figure 7. Renewable energy potential in Sumba island (Winrock International, 2010)

A third site, Lawola, is located on the hillside of the Eastern Sumba district. Although the site requires additional transmission lines to be integrated into the closest grid (Castlerock Consulting, 2015), the Lawola site has great potential for large-scale power generation as it has the highest theoretical wind speed amongst other wind sites. It is also located near Lukat waterfall, which allows a wind-hydro hybrid power generation system to be built there with a total estimated power output of 600,000 MWh per year, or twenty times more than the annual energy demand in Eastern Sumba. Such large-scale energy production could potentially supply not only the entire Sumba island, but also neighboring islands.

Site Name	**Wind speed (m/s)**	**Available Area (m2)**	**Predicted Power (MW)**
Hambapraing	5.0 - 5.5	6,362,737	15.11 – 20.11
	5.5 - 6.3	5,663,640	17.90 – 26.90
Palakahembi	5.0 - 5.5	9,850,657	23.40 – 31.13
Lawola	5.5 - 6.3	10,012,499	31.64 – 47.56
	6.3 - 7.0	1,123,763	5.34 – 7.32
	8.2 - 9.1	3,371,290	35.31 – 48.26

Table 3. Summary of wind energy potential in Eastern Sumba district (Jain, 2015)

A thorough observation was done by measuring wind speeds at Hambapraing site at 60 m elevation from October 2014 to October 2015 (Jain, 2015). Winds typically blow faster at a higher elevation due to fewer obstructions, resulting in less resistance to the air flow. The measured wind speed was later extrapolated with the power law, shown in equation 1, to estimate wind speeds at a selected wind turbine height. v_{ref} represents the wind speed at a reference height, which is the meteorological tower; the Hellmann coefficient (α) represents the wind shear coefficient and captures the meteorological characteristics affecting the wind speed magnitude (climate, weather, terrain, stability of the atmosphere). For Eastern Sumba wind sites, a Hellmann coefficient of 0.20 was selected to represent normal onshore wind condition (Winrock International, 2010).

$$v_{hub} = v_{ref} \left(\frac{h_{hub}}{h_{ref}}\right)^{\alpha} \tag{1}$$

It is a common to find stronger wind speeds during daytime and lower wind speeds during night. This causes a mismatch between wind energy supply and demand, as energy demand is typically at the highest point during night time. Such mismatch could potentially result in power outages with the sudden increase in peak load. Wind speed variation is, therefore, an important factor that should be considered when estimating wind power output. The Weibull model is a powerful tool to capture wind speed variations, using the Weibull probability density (f_w) and cumulative distribution (F_w) to predict hourly wind speed frequency and distribution throughout the year. Weibull functions are outlined in Equations 2 and 3.

$$f_w(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

$$F_w(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{3}$$

Two critical parameters are used as input constants in the Weibull functions: the shape and scale parameters. The shape parameter (*k*) captures variation in the wind speed on an hourly basis, while the scale parameter (*c*) adjusts the Weibull curve with respect to the wind speed threshold (Hiendro et al., 2013). In the Hambapraing wind site, the shape and scale parameters are set to be 3.13 and 7.7 m/s respectively based on a model fitting on the wind speed distribution. The wind speed distribution is generated based on wind speed measurements, wind rose, and wind variation. A wind rose projects the direction in which the wind blows at the strongest circumstances, while wind variation is influenced by weather and climate. This information is important not only to determine if the wind power output is sufficient to satisfy the demand, but also to provide insight on wind turbines positions later to ensure optimum wind power output at all times.

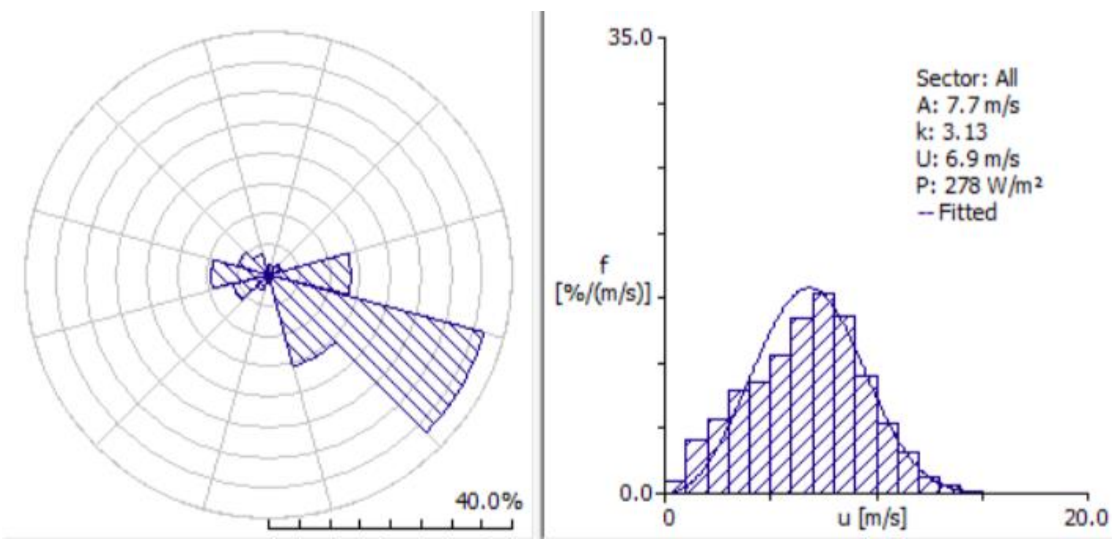

Figure 8. Wind rose direction and wind speed distribution at the Hambapraing wind site, Eastern Sumba (Jain, 2015)

3.2. POTENTIAL WIND POWER OUTPUT IN EASTERN SUMBA

The next step is to obtain the potential wind power output, which is the maximum wind power that could be harvested from the wind site under certain wind conditions. The potential wind power output is measured based on the amount of kinetic energy transferred into mechanical energy by moving the wind turbine blades at a certain time period (hour/second). Thus, wind power output is determined by the wind speed and wind climate conditions. This information can be obtained from the wind speed measurement, wind rose, and wind speed distribution as presented on the previous section. The resulting wind power output is then compared with the theoretical wind power output from Weibull distribution.

$$P = \frac{1}{2}\,\rho\,A\,v^3\,Cp \tag{3}$$

Sector		Wind climate				Power
#	angle [°]	freq. [%]	W-A [m/s]	Weibull-k	U [m/s]	P [W/m²]
1	0	1.5	3.4	2.97	3.00	23
2	30	1.5	3.1	2.25	2.76	22
3	60	2.3	4.1	2.78	3.64	43
4	90	13.6	6.9	3.84	6.26	188
5	120	36.7	8.5	3.89	7.73	353
6	150	15.6	8.6	4.76	7.91	354
7	180	1.3	4.2	1.61	3.78	81
8	210	2.7	5.9	2.19	5.18	149
9	240	6.2	6.7	2.02	5.91	239
10	270	9.6	7.2	2.30	6.39	269
11	300	5.4	7.3	2.03	6.47	312
12	330	3.6	5.3	2.43	4.67	100
All (fitted)			7.7	3.13	6.92	278
Source data					6.71	276

Table 4. Potential wind power output based on the wind rose and wind speed distribution at 60 m elevation at the Hambapraing wind site (Jain, 2015)

The following assumptions were made in calculating the wind power output:

1. Wind power was produced under optimum condition ($C_p = 0.59$)
2. Wind swept area was determined once wind turbine type is selected
3. Air density was measured at 25°C and 1 atm pressure ($\rho_{air} = 1.225$ kg/m^3)

3.3. WIND TURBINE SYSTEM DESIGN

In the pilot operation, the NREL team conducted an analysis of the technical feasibility of integrating a wind power system into the Waingapu grid. The wind power system consists of a single wind turbine with hybrid controller, an energy storage with a capacity of 500 kW, and a diesel generator for backup power with a capacity of 550 kW. The Vestas V52 wind turbine was selected because it has similar power outputs as one of the existing diesel generators (Oswal et al., 2016). The energy produced by wind power system will feed the existing grid substations, Haharu, Kambajawa, and Waingapu, and will be connected to 20 kV transmission lines for distribution to residential and commercial customers (Oswal et al., 2016).

System Characteristics	Wind Turbine Generator (wind power) System
Turbine type	Vestas V52
- **Rotor diameter**	52 m
- **Hub height**	80 m
- **Turbine capacity**	850 kW
Energy Storage	500 kW / 4.17 kWh
Backup Diesel generator	CAT-32/ 550 kW
Hybrid controller	Yes

Table 5. Wind generator system specification (Oswal et al., 2016)

	Diesel generator (current)	Wind power system (planned)
Load capacity (MW)	8.2	0.85
Peak Load (MW)	5.5	5.682

Table 6. Load capacity and peak load for the wind power system and diesel generator (Oswal et al., 2016)

The Vestas V52 turbine provided information about possible wind power outputs based on wind speed as the input parameters, which is plotted in the wind power curve. The wind power curve also contains information about the minimum wind speed (cut-in speed) and the maximum wind speed (cut-out speed) required for the wind turbine to produce optimum output. Using the Vestas V52 wind power curve, the annual energy production (AEP) of the wind power system in Eastern Sumba could be predicted, taking one full year as the time variable. Before matching the measured wind speed with its theoretical wind power output, the wind speed is adjusted for the wind climate information and the suitable turbine hub height. This is necessary to predict the annual energy production as closely to the actual energy production as possible. The annual energy production is estimated to be 2,447,046 kWh per year. Maximum annual energy production using this wind turbine is 7,446,000 kWh, which gives a capacity factor of 32.86%. This capacity factor lies within the normal range of a wind capacity factor of 30 – 40%. This indicates that decent annual wind energy production can be expected in this wind site and that wind turbine should be able to operate optimally.

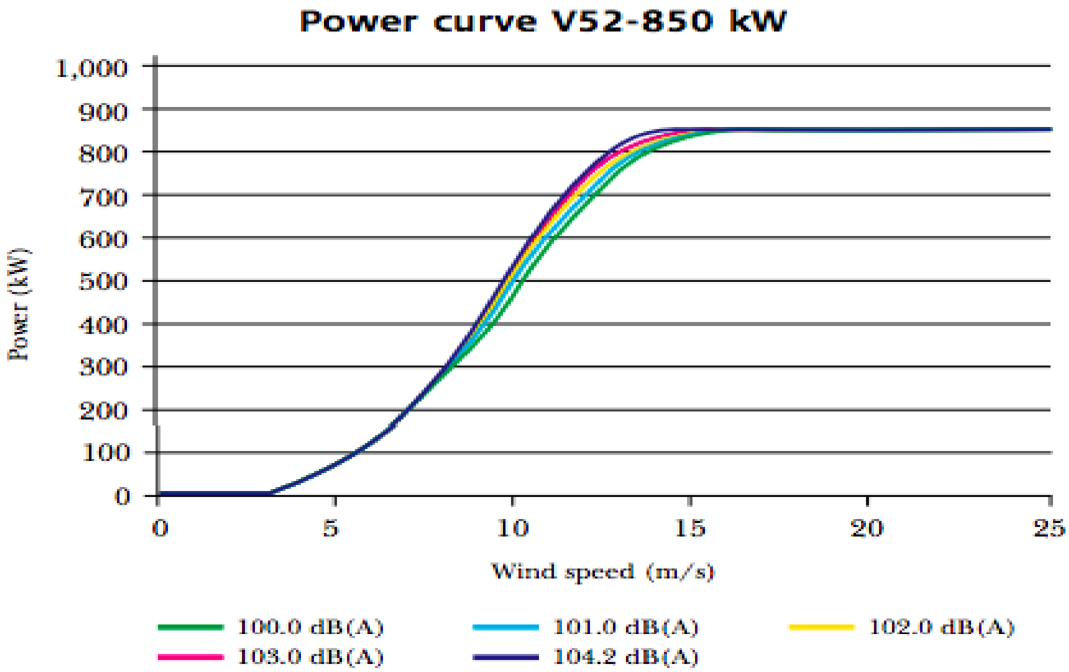

Figure 9. Vestas V52 / 850kW power curve (Vestas, 2005).

3.4. Energy Storage Selections

Although Eastern Sumba wind speed does not vary much throughout the year, it is necessary to maintain grid reliability under all circumstances. This has been accomplished by using a diesel generator as backup power. However, it is important to use a means of energy storage as the main source of power backup rather than the diesel generator, as the objective is to minimize the diesel fuel used in power generation. Energy storage is a critical component in renewable energy generation, particularly in uplifting the value of intermittent energy resources like wind power (Sioshansi, 2011). Because of daily wind speed variations often do not match energy demand, energy storage presents the alternative solution of storing excess wind power output to be dispatched later during peak load times.

In the NREL's wind power system, two types of energy storage from the ABB Powerstore had been considered, Li-ion battery and flywheel storage. Although these types of storage have been widely used in the US, they might not be suitable for implementation in Eastern Sumba due to technical and economic constraints. For this reason, other storage options are considered in the economic analysis of the wind power system. Three other storage types, compressed air storage (CAES), supercapacitor, and pumped hydro storage, were chosen for the following characteristics: efficiency, energy/power capacity, storage lifetime, technology maturity, and capital cost. The Li-ion battery will be replaced with a Pb-acid battery for this study, because Pb-acid battery is available at lower cost while sharing similar characteristics. A pumped hydro system will be considered in spite of exceeding the storage capacity requirement because it might be suitable for a large wind power system, such as the hydro-wind hybrid power generation system.

	Efficiency (%)	**Capacity (MW)**	**Capital ($/kW)**	**Lifetime (Yr)**	**Maturity**	**Charge time**
Flywheels	93–95	0.25	350	~15	Demonstration	Minutes
CAES	70–89	5–400	800	20–40	Commercial	Hours
Pumped hydro	75–85	100–5000	600	40–60	Mature	Hours
Pb-acid battery	70–90	0–40	300	5–15	Mature	Hours
Supercapacitor	90–95	0.3	300	20+	Developed	Seconds

Table 7. Energy storage profile and specifications (Evans et al., 2012).

Chapter 4

Economic Analysis of Wind Power System

4.1. LEVELIZED COST OF ENERGY DEFINITION

Levelized cost of energy (LCOE) is one of the most common cost-benefit measurements for energy projects. The LCOE value for renewable energy systems are often compared with LCOE values for established, conventional power systems, such as the LCOE of coal and gas plants. LCOE takes into account the total project cost and the annual energy production from the power system, with respect to the project lifetime. The LCOE calculation is derived from NREL's Cost of Wind Energy guideline (Mone et al., 2017), which is shown as follows:

$$LCOE = {C_{project}}/{AEP_{NET}} \tag{5}$$

$$C_{project} = CAPEX\,.CRF + OPEX \tag{6}$$

Four main components drive the LCOE value of energy infrastructures: capital expenditures (CAPEX), operational expenditures (OPEX), capital recovery factor (CRF), and net annual energy production (AEP_{NET}). All elements are annualized with respect to the project lifetime (Mone et al., 2017). Each component will be furthered discussed in the following sections.

4.1.1. Capital Expenditures (CAPEX)

Capital expenditures (CAPEX) accounts for all initial costs required to construct any the energy infrastructure. Figure 10 depicts the CAPEX structure for the wind power system. Two major components are explored further in the cost analysis: equipment cost, which accounts for 70% of the CAPEX value, and the balance of system (BOS), which accounts for 20% of CAPEX value. The remaining 10% consists of miscellaneous expenses that are less significant in the CAPEX valuation ant thus can be disregarded in the economic analysis.

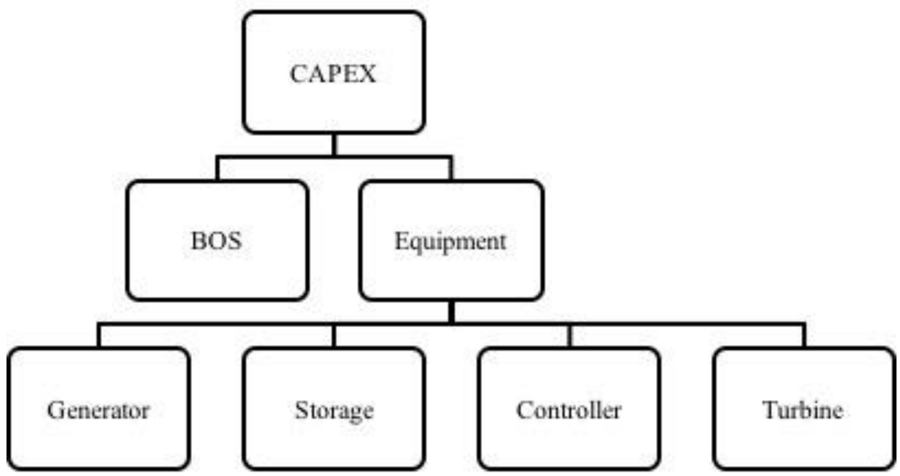

Figure 10. Capital expenditures components for wind power system

Equipment cost includes all hardware installation cost, such as the turbine, controller, storage, and diesel generator cost. The turbine and controller are considered as one cost unit and its value is obtained from the NREL's System Advisor Model (SAM) database. Diesel generator exists in the current power generation system; thus, it is assumed to be available at no cost. Table 8 shows the range of equipment costs based on the type of storage selected, as previously specified in Chapter 3, at a 500-kW storage capacity. Storage costs range from $150,000 for the supercapacitor and Pb-acid battery, to $400,000 for compressed air. The average storage cost is $ 235,000, and this value is used to give a total equipment cost of $2,585,250 or $3,041.47/kW of wind power system installation.

Cost Structure	Types of Energy Storage				
	Flywheel	Pumped hydro	CAES	Supercapacitor	Pb-acid battery
Storage	$ 175,000	$ 300,000	$ 400,000	$ 150,000	$ 150,000
Turbine and controller	$ 2,350,250	$ 2,350,250	$ 2,350,250	$ 2,350,250	$ 2,350,250
Diesel generator	$ -	$ -	$ -	$ -	$ -
Equipment cost	$ 2,525,250	$ 2,650,250	$ 2,750,250	$ 2,500,250	$ 2,500,250
Cost per kW power system	$ 2,970.88	$ 3,117.94	$ 3,235.59	$ 2,941.47	$ 2,941.47

Table 8. Equipment cost based on the types of energy storages

Meanwhile, the balance of system (BOS) accounts for construction and land management costs, which include raw material and labor wages, which are more liquid than the equipment cost. As with the wind turbine cost, the balance of system value is obtained from the NREL's System Advisor Model database, adjusting for the Indonesian gross domestic production (GDP). Construction cost tends to be less expensive in Indonesia due to the lower material, labor and land permit cost. The balance of system value obtained from System Advisor Model database was generated considering construction in the US with higher material and labor costs, in addition to more expensive and complex land management costs. Transmission and distribution costs are omitted from cost estimation calculation, since existing transmission lines will be used for grid connection, eliminating the need for new transmission and distribution infrastructures (Oswal et al., 2016).

Based on the equipment and the BOS cost, the CAPEX value is estimated to be $3,284,195 or $3,863.47/ kW for the wind power system. This is more than twice the average land-based wind CAPEX in the United States, which is $1,690/kW for 2.0 MW wind farm size (Mone et al., 2015). The high CAPEX value can be explained by the small scale of the pilot project (<1 MW), which means the project did not reap benefits from economics of scale. Planning for a larger capacity wind power system should resolve this issue, producing lower CAPEX value per kW.

CAPEX Structure	Unit Price ($/kW)	Total Expenses ($)
Equipment Cost	$ 3,041.47	$ 2,585,250
Balance of System	$ 822.00	$ 698,945
Capital Expenditures	**$ 3,863.47**	**$ 3,284,195**

Table 9. Capital expenditures for 850 kW wind power system

4.1.2. Operational Expenditures (OPEX)

Operational expenditures (OPEX) account for the operation and maintenance costs of the project throughout its lifetime. The OPEX value mainly consists of the fuel and labor cost for each component of the wind power system, including the wind turbine, storage, and diesel generator. In terms of the wind turbine, fuel cost is insignificant because wind kinetic energy has replaced the need for fuel combustion. The wind turbine OPEX value, however, is still higher than the regular wind turbine OPEX due to the following reasons:

1. Indonesia has little experience in wind power generation; capital is thus required for training, technical support, and maintenance (Castlerock Consulting, 2015).
2. Sumba is a rural, isolated island, and logistic costs are predicted to be more expensive as replacement materials must be imported from outside the island.
3. This pilot project is categorized as a small-scale operation (< 1MW) and thus, did not benefit from economies-of-scale.

The wind turbine OPEX value is estimated to be $20/ kW, obtained from similar rates of other wind turbine installations in Indonesia (Jonan and Tørnæs, 2015). This value compensates for the higher maintenance cost with the lower labor wages (Jain, 2015). With regards to the storage OPEX, the value is estimated to be 30% of the storage CAPEX (Hiendro et al., 2013). The diesel generator OPEX, on the other hand, is calculated at 5% of total wind power system OPEX value under the stipulation that unsubsidized diesel fuel price will be used to generate backup power (Oswal et al., 2016). A discrepancy in the percentage value of the storage and diesel generator OPEX is due to the differences in how frequent the technology will be used in the system. It is hoped that the energy storage will be used at higher frequency, with the diesel generator being used when both the wind turbine and the energy storage are unable to fulfill the increasing energy demand.

The total wind power system OPEX is estimated to be $229,390 or $270/kW of generation. This is much higher than the regular OPEX value (Mone et al., 2015) because the regular OPEX does not consider the use of energy storage and diesel generators as sources of backup power. Again, economy-of-scale could potentially reduce the OPEX value with respect to the kW of installed wind power system.

OPEX structure	Unit Price ($/kW)	Total Expenses ($)
Wind turbine	$ 20	$ 17,000
Energy storage	$ 141	$ 70,500
Diesel generator	$ 258	$ 141,890
Operational Expenditures	**$ 270**	**$ 229,390**

Table 10. Operational expenditures for 850 kW wind power system.

4.1.3. Net Annual Energy Production (AEP_{NET})

The annual energy production calculated in the previous chapter does not consider systematic loss that will happen throughout the operation of the wind power system. Thus, the annual energy production needs to be adjusted for different types of power loss, which will be reflected in the net annual energy production (AEP_{NET}). 10% of the system loss for this wind power system is assumed based on the standard wind turbine loss (Jain, 2015), giving an AEP_{NET} value of 2,202,342 kWh. The capacity factor is also re-adjusted based on the net annual energy production to give a value of 29.58%, which is slightly lower than the average wind capacity factor of 30-40%. This indicates although the wind power system is expected to produce a sufficient energy output under normal conditions, the system may struggle to meet demand during unexpected increases in the peak load. This underlines the need for sources of backup power such as energy storage and diesel generators to ensure system reliability.

AEP Structure	Value (kWh)
AEP_{MAX}	7,446,000
AEP_{GROSS}	2,447,046
System loss	244,705
AEP_{NET}	**2,202,342**
Capacity factor (%)	**29.58%**

Table 11. Annual energy production for 850 kW wind power system

Furthermore, the capacity factor can be improved by increasing the size of the wind farm, extending the hub height to capture higher wind speed, and utilizing wind turbines with a larger capacity. For instance, a wind site in South Sulawesi, who experiencing similar wind speeds to the site in Eastern Sumba, boasts a capacity factor of 40%, or 25% higher than the capacity factor in the Eastern Sumba. This can be explained by South Sulawesi's larger scale wind farm, with capacity of 10 MW from multiple 2 MW wind turbines. (Jonan and Tørnæs, 2017). An increase in the capacity factor will result in a higher wind power output and therefore a higher AEP_{NET} even if the site does not possess strong wind speeds (higher than 10 m/s). As there is an inverse relationship between annual energy production and the LCOE value, the LCOE can be reduced significantly.

4.1.4. Capital Recovery Factor (CRF)

Since the CAPEX consists primarily of upfront cost of the wind power system, it needs to be annualized to match the OPEX and the AEP_{NET} values that are estimated on an annual basis. Hence, the CAPEX value is discounted to the present value by using the capital recovery factor (Nelson et al., 2006). Discounting the CAPEX value also allows current monetary conditions affecting economic feasibility to be captured as well. This valuation would provide insight into whether the wind power system can be implemented under current economic condition.

The capital recovery factor (CRF) is estimated based on the methodology outlined in the System Advisor Model, which is presented in Equation 7. The CAPEX value will be discounted using the weighted average cost of capital (WACC) using 20 years as of the wind power system's lifetime. The WACC encapsulates the project's cost of capital weighted against on the project's funding source: equity and debt. Because all natural resources are owned by the government, equity and debt in this project are assumed to belong to the government. The WACC is specifically adjusted to take the inflation rate into account to capture national economic conditions that may influence the government's ability to execute this project. Indonesia might gain some benefits in the inflation-adjusted WACC value due to its high inflation rate. A high inflation rate should encourage the government to invest more in new infrastructure, as by investing in new infrastructure the government may induce a higher frequency of money circulation, expedite economic growth, and increase the consumer purchasing power (Klein, 2015).

$$CRF = \frac{WACC}{1-(\frac{1}{1+WACC})^t} \tag{7}$$

$$WACC = \frac{1+[EF.((1+r_e).(1+i)-1)]+DF.[((1+r_d).(1+i)-1)].(1-T)}{1+i} - 1 \tag{8}$$

$$r_e = \frac{1+ROI}{1+i} - 1 \; ; \; r_d = \frac{1+r_{loan}}{1+i} - 1 \tag{9,10}$$

The WACC consists of two parts: cost of equity (r_e) and cost of debt (r_d). Both rates are weighted based on the debt/ equity ratio and are individually adjusted for the current inflation rate. The cost of equity, taken as the return on investment (ROI), is obtained from the 10-year Treasury Bond rate of return from the Bank of Indonesia, the national bank that is responsible for releasing bonds to fund infrastructure and other investments. Meanwhile, cost of debt is obtained from the Bank of Indonesia's 2017 loan rate (r_{loan}). The cost of debt is further adjusted with the tax rate (T) of 28% in compliance with the Ministry of Finance's regulation of new energy infrastructure (Kamal et al., 2015). The debt fraction (DF) is chosen to be 80% as new infrastructures have mostly been financed with aids and loans from the foreign institutions, such as Asian Development Bank. As the result, the equity fraction (EF) is taken at 20%.

CRF Structure	Regular WACC	Inflation-adjusted WACC
IRR	11.00%	11.00%
Debt rate	11.60%	11.60%
Tax rate	28%	28%
Debt Fraction	80%	80%
Equity Fraction	20%	20%
Inflation rate	0.00%	3.18%
WACC	10.86%	5.53%
CRF	**0.124**	**0.084**

Table 12. Capital Recovery Factor (CRF) for wind power system with regular weighted average cost of capital (WACC) and the inflation-adjusted WACC.

Comparing the CRF values from regular WACC and the inflation-adjusted WACC, it is verified that inflation rate significantly reduces CRF value. Adjusting the WACC value with approximately 3% of inflation rate dropped the WACC value from 10.86% to 5.53%, resulting in a 50% reduction of CRF value. A 5% WACC value usually indicates an established project with low risk, which is completely the opposite nature of this project that carries high risk and potentially high return of investment. However, the inflation-adjusted WACC has brought the project to possess lower risk yet maintained high expected return. This is critical in enhancing this wind power system project to be a more compelling investment for the private sector. It potentially drives the national and regional economy to grow faster, which is hoped to increase local purchasing power and to provide higher return of investment for investors.

4.2. LCOE Analysis for Wind Power System

Once all LCOE elements have been determined, the levelized cost of energy (LCOE) for the wind power system could be estimated, along with the comparison with the LCOE values for the diesel generator using subsidized and unsubsidized diesel fuel. LCOE for diesel generator was calculated in the similar way as the LCOE for the wind power system, which includes the following components: CAPEX, OPEX, CRF, and AEP_{NET}. The CAPEX for a diesel generator is obtained from the capital cost of the Caterpillar CAT-32 diesel generator. This generator has a capacity of 880 kW and is currently used to generate power for the Waingapu grid, the main grid in Eastern Sumba district. While the diesel generator size is 30kW higher than the wind turbine system size, only 850 kW of diesel generator capacity is used and the system comparison is still valid.

The OPEX value is mainly derived from the diesel fuel cost, which is determined by multiplying the required diesel fuel volumes to generate power with the retail diesel fuel price. The unsubsidized diesel fuel price ranges from $1.00 to 1.50 / liter during dry season and $2.00 – 2.50 / liter during wet season (Winrock International, 2010), while the subsidized fuel price is maintained at $0.38 / liter (Pos Kupang, 2017). It was evident that the fuel subsidy has been ranging from $0.62 - $2.12 /liter, which will be eliminated with the implementation of the wind power system. Because the CRF value is independent of system technology, the same CRF value is also used to discount the diesel generator CAPEX into its present value. The annual energy production for diesel generator is estimated from the generator capacity with 35% system efficiency, assuming the generator runs continuously throughout the year (Blum et al., 2013).

	Wind power system	**Diesel generator (w/o fuel subsidy)**	**Diesel generator (w/ fuel subsidy)**
System size (kW)	850	880	880
AEP_{NET} (kWh)	2,202,342	2,698,080	2,698,080
CAPEX ($)	$ 3,284,195	$ 898,945	$ 898,945
OPEX ($)	$ 229,390	$ 3,107,485	$ 837,243.85
CRF	0.084	0.084	0.084

Table 13. LCOE components for wind power system in comparison to the diesel system with subsidized and unsubsidized diesel fuel.

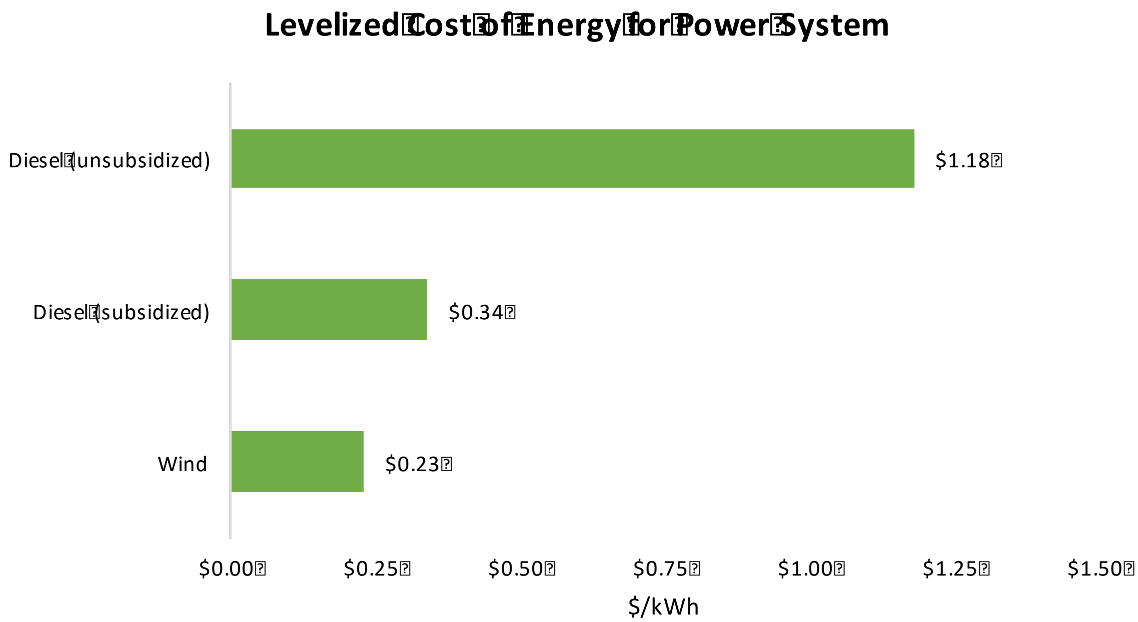

Figure 11. LCOE Analysis for wind power system (wind) and diesel generator system (with subsidized/ unsubsidized fuel).

By replacing the diesel generator with a wind power system while using the unsubsidized fuel, the LCOE value drops from $1.18/kWh to $0.23/kWh. This translates to over 80% reduction of power generation cost. The LCOE for the wind power system is surprisingly lower than the diesel generator LCOE with subsidized fuel. Looking closely to the LCOE components, it is clear that the main cost difference between the wind power system and the diesel generator is the OPEX value. The OPEX value for wind power system is ten times lower than the diesel generator OPEX with unsubsidized fuel. As for the diesel generator with subsidized fuel, the lower OPEX value in the wind power system is offset by the significantly higher CAPEX value, which explains why the LCOE value for a diesel generator with subsidized fuel is not much different than the LCOE value for a wind power system. However, the use of diesel fuel still affects the OPEX cost continuously, such that larger disparity of total generation cost between the wind power system and diesel generator is expected to occur in the long run.

Another determining factor is that the diesel systems produce slightly higher energy than the wind power system. This is due to the intermittent nature of wind power generation that results in variation of wind power output generated throughout the year. While in the calculation the diesel generator is expected to produce constant amount of energy per year thus exceeded the performance of the wind power system, the diesel fuel supply often got disrupted in Eastern Sumba due to unexpected weather conditions. This has placed diesel fuel in the similar position as the intermittent energy resources. To leverage the wind power system positions against the diesel generator, the energy production from the wind power system could be increased and stabilized, increasing hub height to capture higher wind speed, and potentially extending the wind power system installation to cover the offshore areas if possible.

4.3. SUBSIDY ANALYSIS

The subsidies in this project refer to any types of energy subsidies applied onto the power system to ensure that energy, including fuel and electricity, is accessible to Eastern Sumba inhabitants at affordable rates. The subsidy value is evaluated based on the customer purchasing power for energy products, such as electricity and fuel. The purchasing power corresponds to the GDP rate, such that a region with low GDP rate like Eastern Sumba is expected to have a low purchasing power and high energy subsidies.

The energy subsidy is divided into two types: fuel subsidy and electricity subsidy. The fuel subsidy is placed to maintain fuel price at constant rate despite the oil and gas market volatility, while the electricity subsidy is set to prevent electricity price volatility due to the change in the inflation rate. In this analysis, fuel subsidy only applies to the diesel generator system with subsidized fuel, whereas other systems are assumed to use the unsubsidized diesel fuel. Fuel subsidy is estimated by taking the LCOE difference between diesel generator systems with and without the subsidized fuel. For the electricity subsidy, the value is measured by subtracting the LCOE value with the current electricity price in Eastern Sumba, which is set to be $0.08/kWh (PLN, 2016).

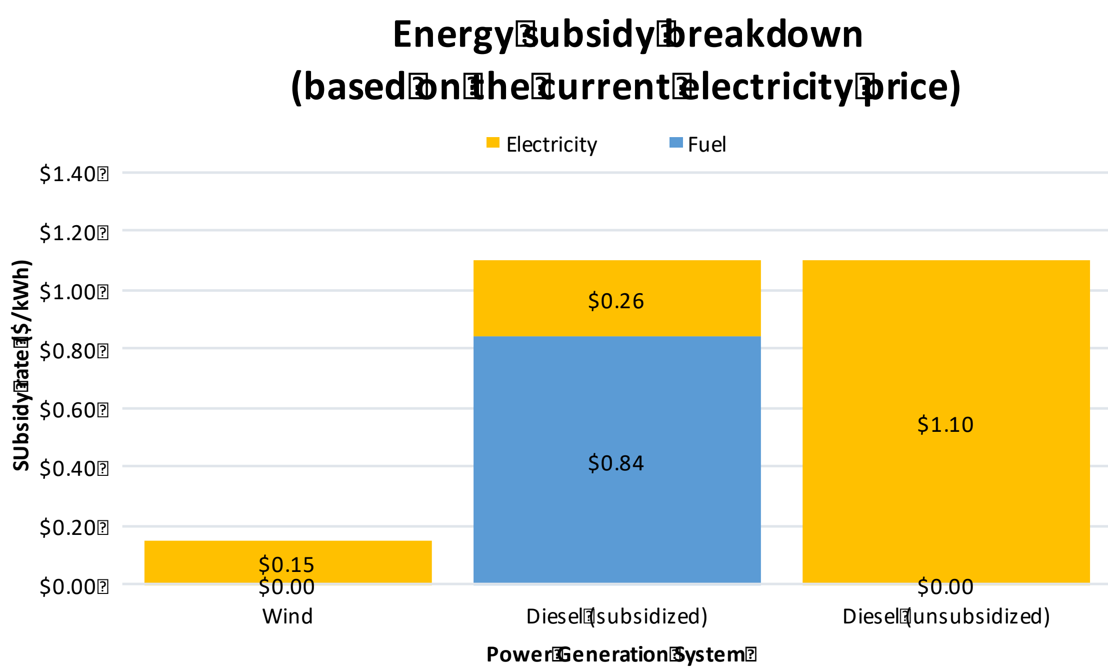

Figure 12. Energy subsidy structures for wind power and diesel generator systems (with unsubsidized / subsidized fuel)

The advantage of the wind power system is highlighted further in the subsidy analysis. The energy subsidy rate sharply declines from $1.10/kWh for diesel generator systems to $0.15/kWh for the wind power system. This means that over 86% of subsidy reduction could be achieve by simply replacing the diesel generator with the wind power system. Looking closely at the subsidy structures, it is evident that the fuel subsidy is completely eliminated with the use of wind power as the main source of the power generation system. The electricity subsidy is also less for the wind power system at $0.15/kWh or $328,612.31, whereas the electricity subsidy for the diesel generators were observed to be $2,967,023.73 without subsidized fuel and $701,500.80 with subsidized fuel. The wind power system is not only successful in eliminating the fuel subsidy, but also in cutting the current electricity subsidy by $372,888.49 or over 50%. In a nutshell, the government saves approximately $ 2,638,411.43 by simply changing the power generation system from single diesel generator with the equivalent wind power system in one power plant. If the wind power system completely replaces all diesel generators used in Eastern Sumba, it is possible that energy subsidy is no longer needed in the long run, which saves the government a lot of money to be allocated in more critical sectors, such as healthcare and education.

	Diesel generator system	**Wind power system**
Energy subsidy ($/kWh)	$ 1.10	$0.15
Total Energy Production (kWh)	2,698,080	2,202,342
Total Energy Subsidy ($)	$ 2,967,023.73	$ 328,612.31
Subsidy reduction ($)	**$ 0.00**	**$2,638,411.43**

Table 14. Potential subsidy reduction by using wind power system for power generation

4.4. PAYBACK PERIOD ANALYSIS

The last method to confirm the economic feasibility of this wind power system infrastructure is through the payback period. The simplified payback period is generated by dividing the LCOE value with the electricity price, which act as the cost and revenue of the project respectively. The LCOE value has been adjusted to the present value and considered to be the total cost of the generation system. Meanwhile, the electricity rate is assumed as the main revenue from this power generation, since the power market is completely regulated. The feed-in tariff is not considered as revenue because Indonesia has not yet established any fixed feed-in tariff and is currently determined based on the negotiation between the government and the independent power companies (PwC Indonesia, 2017). Based on the payback period calculation, it is evident that the wind power system has the shortest payback period at 3 years. Thus, the government is expected to receive profit starting from three years of wind power system operation up to the twenty years of its lifetime.

	Wind power system	**Diesel generator (subsidized)**	**Diesel generator (unsubsidized)**
Revenue ($/kWh)	$0.08	$0.08	$0.08
Cost ($/kWh)	$0.23	$0.34	$1.18
Payback period (years)	3	4	15

Table 15. Payback period (in years) for wind power system in comparison to the diesel system with subsidized and unsubsidized diesel fuel.

Chapter 5

LCOE Sensitivity Analysis and Potential Reduction Scenarios

5.1. LCOE SENSITIVITY ANALYSIS WITH MONTE CARLO SIMULATION

Overall, the wind power system is feasible for current implementation and gives more economic advantages considering a lower total generation cost, a significant subsidy reduction, and a shorter payback period. While it is a compelling system to be implemented, it is important to understand how each of the LCOE components affect the LCOE value and to investigate if any LCOE component reduction might drive the LCOE value to be breakeven with the current electricity rate, to lower the subsidy rate as close to zero as possible, and to shorten the payback period. This could be achieved by examining the LCOE sensitivity using the Monte Carlo simulation. Monte Carlo simulation is a mathematical technique for analyzing potential risks in investments, corporations, or projects. A range of random values is simulated based on the range of input parameters to obtain a probability distribution of possible outcome values based on thousands of recalculations (Palisade, 2018).

The Monte Carlo simulation model for this thesis study was built by using @Risk program, an add-in tool in Microsoft Excel (Williams et al., 2008). LCOE elements, such as CAPEX, OPEC, CRF, and AEP_{NET} are used as input parameters, while the LCOE value is set as the sole output parameter in this sensitivity analysis model. Because each LCOE component has been previously determined in the single value format, uncertainties are introduced into the LCOE components to create a range of values for the input parameters.

A 5% uncertainty is applied to all LCOE components to give a 90% confidence level in the input parameters. This also applies to the 90% confidence interval in the output parameter, which is the LCOE value. All LCOE components are assumed to have a uniform distribution (Ismail et al., 2015). The sensitivity analysis of the LCOE value with respect to the LCOE components as the input parameters are presented as a probabilistic distribution with 10,000 iterations of possible input parameter combinations.

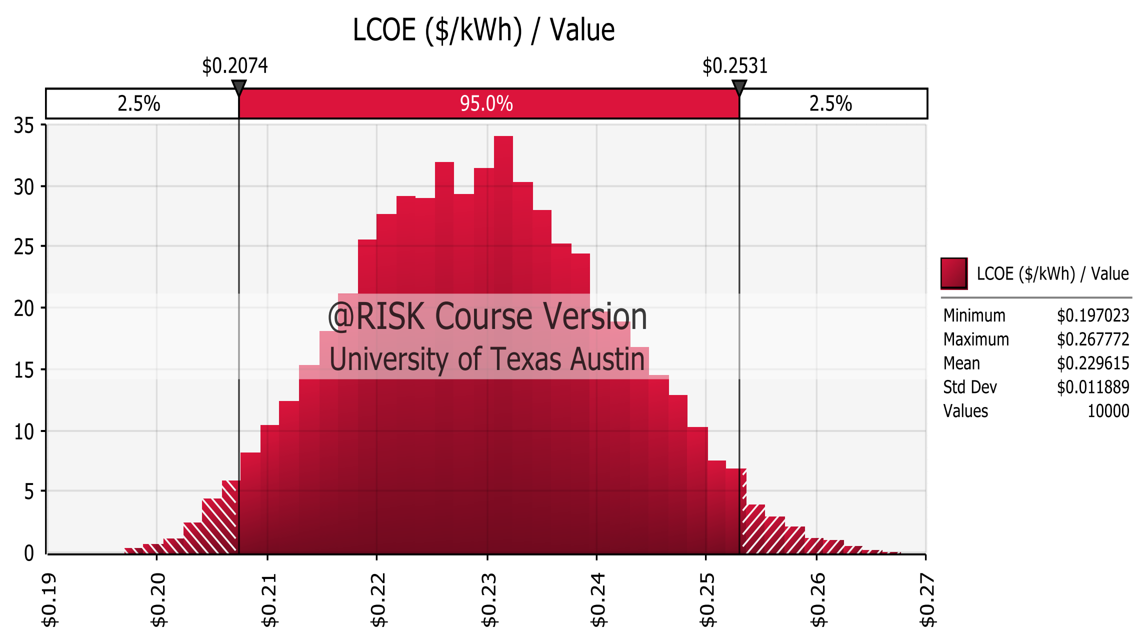

Figure 13. LCOE probability distribution for wind turbine generation (wind power) system with 95% confidence interval

The LCOE value varies from $0.21 to $0.26 or 10% of its original value at 95% confidence interval by taking 5% uncertainties on each of the LCOE components. Despite having an equal amount of uncertainties, each of the LCOE components behave differently to influence the LCOE value. A tornado chart of the input parameter effects on the LCOE output has been generated to capture the impact of individual LCOE components to the LCOE variation. It was observed that the CRF has the most significant impact to the LCOE output. CRF value consists of multiple factors, such as tax, debt/ equity fraction, loan rate, inflation rate, and so on. It also controls the CAPEX value, which is the largest numerical value in the LCOE composition. For these reasons, the CRF holds a critical value in influencing the LCOE. Reducing CRF value by 5% drives the LCOE value to $0.216, or 6% lower than the original LCOE. In contrast, the OPEX has a relatively small impact to the LCOE in comparison with other LCOE components, such that a change in OPEX value has little effect on the overall LCOE. For instance, a 5% reduction of the OPEX value only changes the LCOE value by 2%.

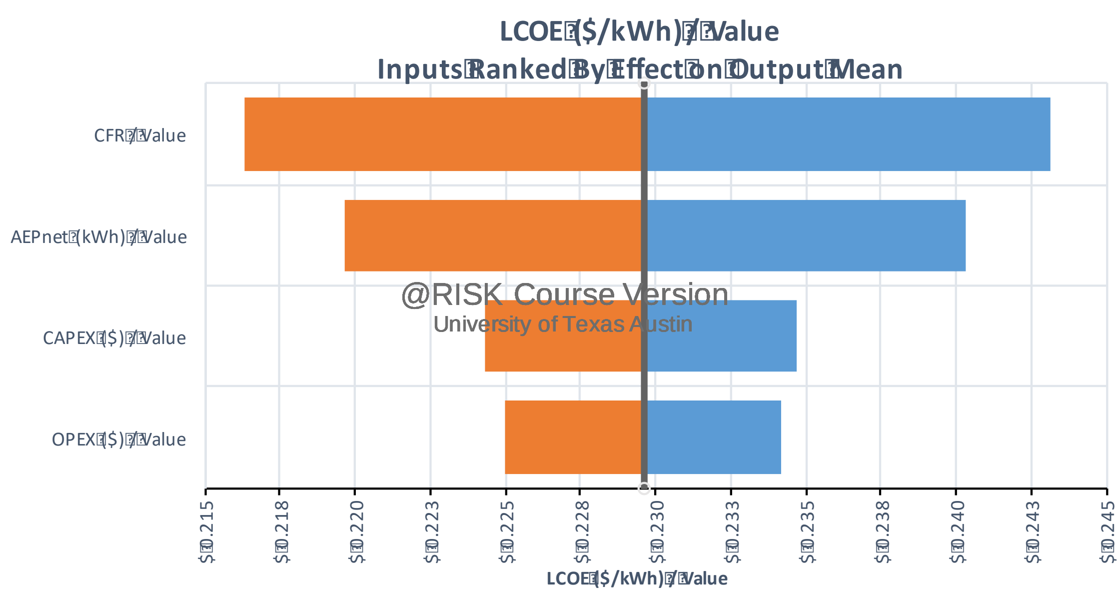

Figure 14. LCOE component effect on the LCOE value, representing as a tornado chart

A regression analysis was conducted to show individual interactions between each LCOE component with the LCOE value. The regression coefficient represents the significance of each LCOE component in driving the LCOE value. It was verified that the CRF has the most robust impact on the LCOE value, followed by CAPEX and OPEX value. AEP_{NET} has a reciprocal effect to the LCOE value, since higher energy production implies more efficient power system operation, thus lowering the LCOE value. By reducing the CRF and CAPEX values, as well as increasing AEP_{NET} value, a LCOE rate of $0.08/kWh is not impossible to be achieved. The next section will determine how much LCOE component reduction is required to achieve the least LCOE value with the lowest subsidy rate and the shortest payback period.

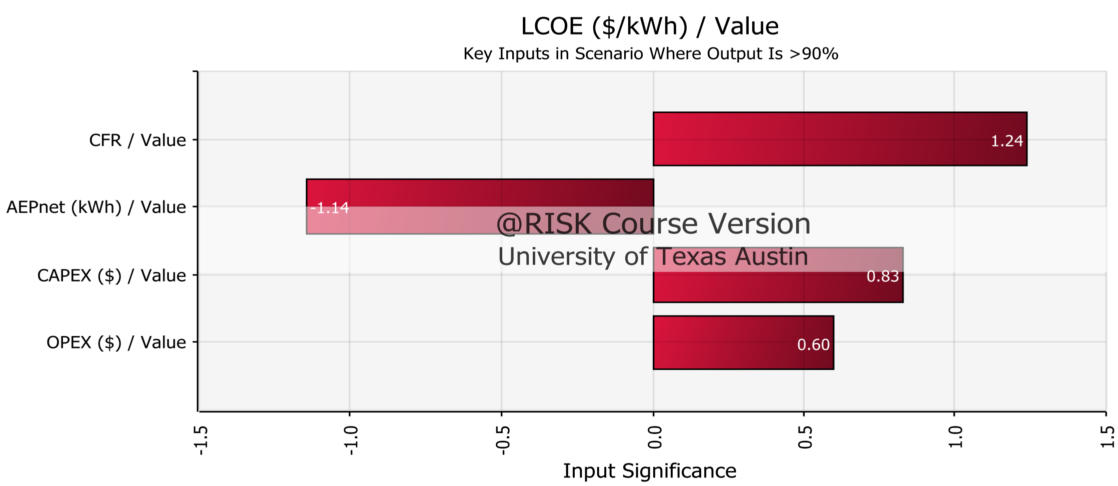

Figure 15. LCOE regression analysis based on each LCOE components

5.2. LCOE Least Cost Scenarios

Two types of LCOE least-cost scenarios are generated to bring the LCOE as close to the current electricity rate as possible. Each scenario proposes a change in the following

LCOE components as the main drivers of the cost reduction: CRF and CAPEX. Both components have been selected because they affected the LCOE value the most according to the sensitivity and the regression analysis. The scenario to increase AEP_{NET} production is not pursued because it requires further technical assessment and site evaluation, which is beyond the scope of this thesis. Meanwhile, the change in OPEX will be omitted as it has the least impact to the overall LCOE value. Results from both scenarios will be compared based on how effective they are in reducing the LCOE value while lowering the subsidy rate and shortening the payback period.

5.2.1. CRF reduction scenario

In the LCOE least-cost scenario with CRF reduction, two main CRF variables, tax rate and loan rate, will be reduced at a similar percentage while maintaining other variables at constant values. The tax rate and loan rate are selected as the independent variables because they could be manipulated by the government through tax incentives and/or a soft loan rate for new energy infrastructures. The debt and equity fraction will not be changed any further, as it is risky to exercise a project with 100% debt when it is impossible to run the project at 100% government equity. The inflation and return of investment are mainly controlled by the market, and thus, would be challenging to adjust them into the desirable rates. The amount of reduction required in the tax and loan rates are defined by performing an iteration analysis using Excel solver in which the CRF is set at minimum value. Some positive values in the intermediate outcomes, such as WACC, inflation-adjusted cost of debt, and inflation-adjusted cost of equity, is set as iteration boundaries to maintain realistic

LCOE nominal. It was observed that a 72.6% reduction of debt rate and tax rate gives a minimum CRF value of 0.057, which is a 31.7% decline from the previous CRF value of the wind power system.

CRF Structure	LCOE base cost	LCOE least-cost scenario
Reduction rate	0.00%	72.59%
Debt rate	11.60%	3.18%
Tax rate	28%	7.67%
IRR	11.00%	11.00%
Debt Fraction	80%	80%
Equity Fraction	20%	20%
Inflation rate	3.18%	3.18%
WACC	5.53%	1.33%
CRF	**0.084**	**0.057**

Table 16. LCOE least-cost scenario for wind power system through CRF reduction

5.2.2. CAPEX reduction scenario

Wind installation costs have had a major decline in the last few decades, from $5,000/kW in 1983 to $1,500/kW in 2017 (IRENA, 2018). Technology development and the rise in the amount of installed wind capacity have successfully dropped the wind installation cost worldwide. Assuming the similar reduction rate for wind turbine and controller CAPEX, it could be projected that the wind CAPEX will reach the $1,000/kW level in the next ten years.

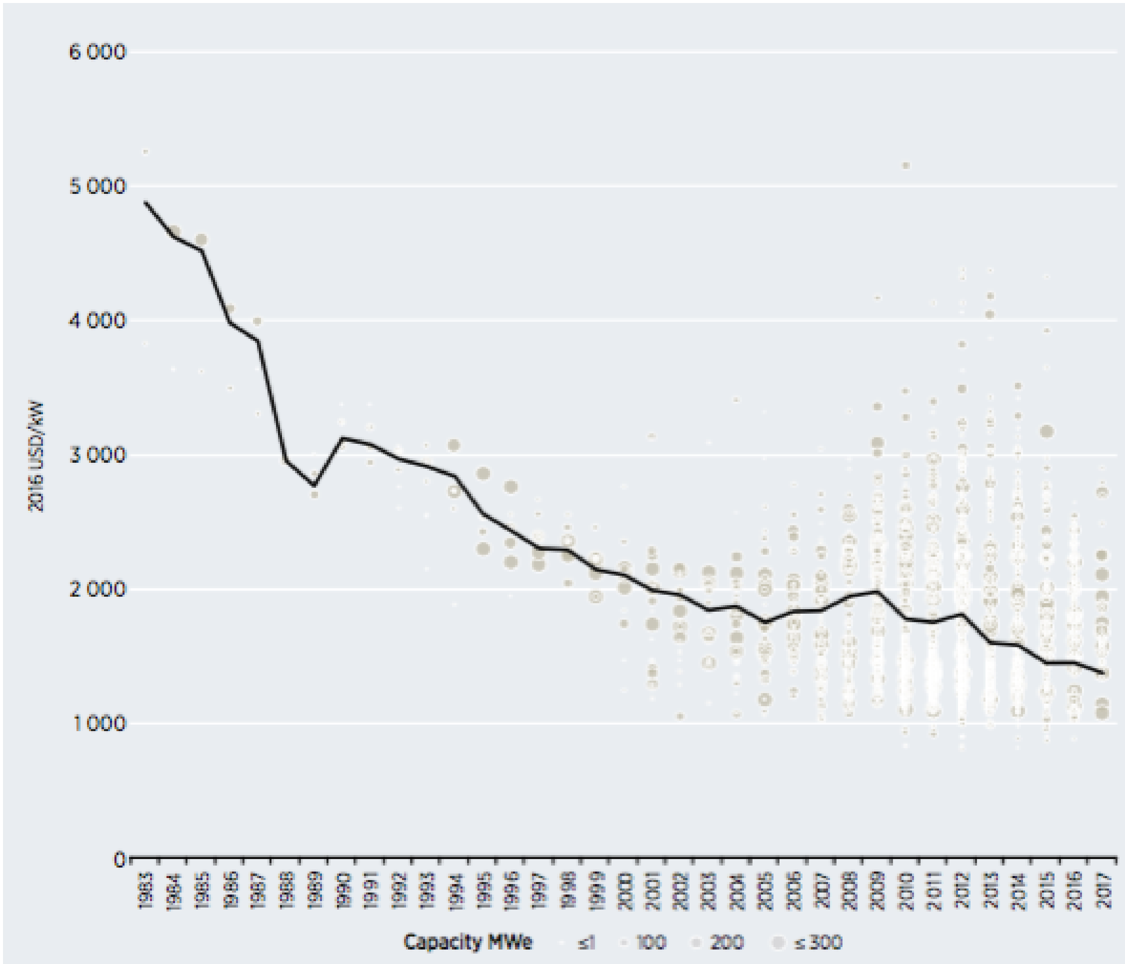

Figure 16. Total installed cost of onshore wind projects and global weighted average in 1983-2017 (IRENA, 2018)

Again, the iteration analysis in Excel solver is used to determine the percentage of CAPEX reduction required to reach the CAPEX minimum value of $1,000/kW. This produces a CAPEX value of $1,000/kW with wind turbine CAPEX reduction of 63.8%. Holding the energy storage cost and balance of system at constant value, the new CAPEX value for the wind power system is estimated to be $2,292/kW, or 40.7% less than original CAPEX value. This could be achieved under three condition: (1) exercising the project in later years when wind turbine cost has reached $1,000/kW, (2) constructing a larger wind power system to reach the desirable CAPEX value with economies of scale, and (3) applying CAPEX upfront rebate for wind turbine construction.

	LCOE base cost	LCOE least-cost scenario
Turbine + controller	$2,765	$1,000
Storage	$470	$470
Diesel generator	$0	$0
Equipment cost	$3,235	$1,470
Balance of System	$822	$822
CAPEX	**$3,864**	**$2.292**

Table 17. LCOE least-cost scenario through CAPEX reduction

5.3. ECONOMIC ANALYSIS ON THE LCOE LEAST-COST SCENARIO

The previous economic indicators, such as LCOE, subsidy rate, and payback period are used once more to evaluate the effectiveness of each scenario in turning the wind power system to become more feasible for current implementation and compelling for future investors. This time, the economic indicator values from each scenario are compared against the LCOE base cost from previous chapter and are evaluated against each other as well. Both scenarios have successfully lowered the LCOE, subsidy rate, and payback period values at similar rate. The slight difference observed on the LCOE and subsidy rate between the CAPEX reduction scenario and the CRF reduction scenario lies in the robustness of the CAPEX and CRF components in changing the CAPEX and CRF value respectively. For instance, the tax and loan rates have less impact to reduce the CRF value in comparison to the impact of the decline in wind turbine cost to the CAPEX value in the wind power system. It is important to note that the wind turbine cost holds the largest share of the CAPEX value, such that more rigorous decline is expected from the CAPEX reduction scenario rather than the CRF scenario.

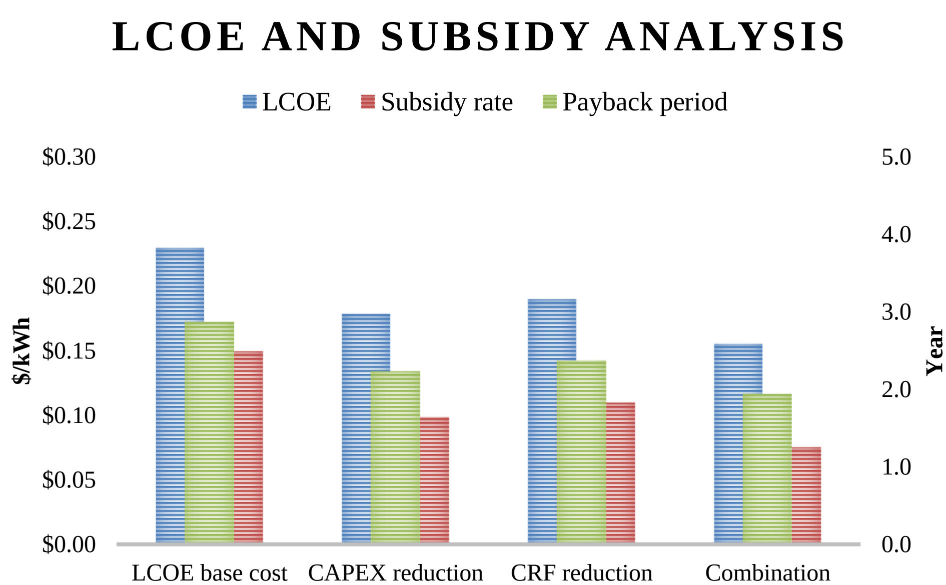

Figure 17. LCOE, subsidy analysis, and payback period for LCOE least-cost scenarios

Regardless, LCOE produced in both scenarios have not yet reached the current electricity price. Hence, a third scenario is proposed to see if a combination of CAPEX and CRF reductions could drive the LCOE closer to the current electricity price. A 31.7% CRF reduction is paired with the 40.7% CAPEX reduction to give a LCOE value of $0.15. While the result is not exactly cumulative, this scenario has managed to lead the LCOE value to reach the closest value to the current electricity price with the least subsidy rate at

$0.07/kWh. It is also noticed that this scenario lowers the LCOE and subsidy rate of the base scenario by 35% and 50% respectively, while cutting the payback period to 1.9 years.

While the LCOE have yet to reach the current electricity price, the combination of CRF and CAPEX reduction has managed to produce a low LCOE value in comparison to the regular wind power system LCOE, let alone the diesel generator LCOE. It also cuts the energy subsidy to be $163,941.18, or 94% less than the current energy subsidy placed in Eastern Sumba power generation. This brings the government one step closer to eliminating the energy subsidy, which could be allocated for providing rebates and incentives in making renewable energy generation more cost-effective and encouraging investments from the private sector as well.

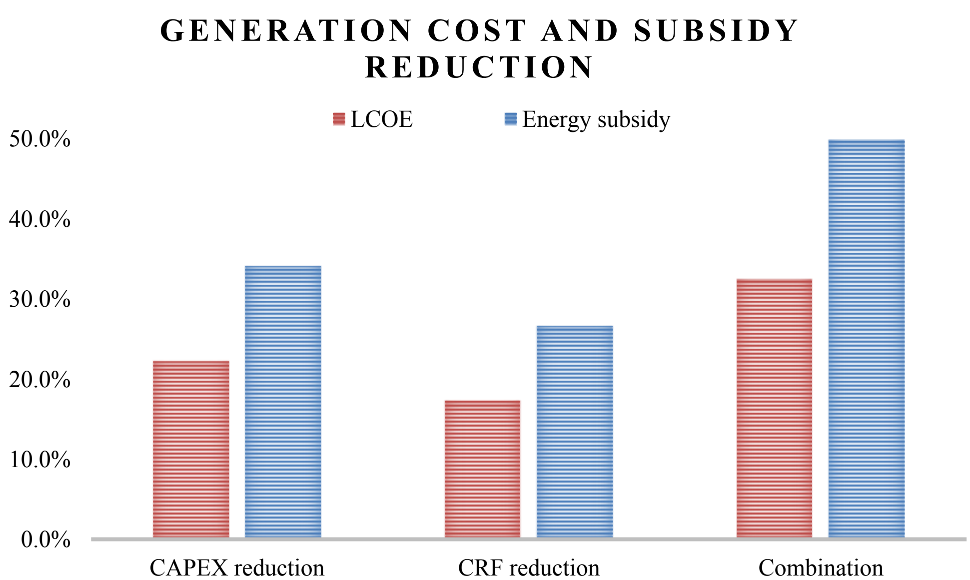

Figure 18. Potential LCOE and subsidy reductions based on LCOE least-cost scenarios

Chapter 6

Conclusion and Recommendation

An economic analysis has been performed to investigate the costs and benefits of integrating an 850-kW wind power system to replace the single diesel generator in the Eastern Sumba grid. Three economic indicators, LCOE, subsidy rate, and payback period were used to measure the economic feasibility of implementation of the wind power system under the current economic conditions in Indonesia. The LCOE and subsidy rate for the proposed wind power system is \$0.23/kWh and \$0.15 kWh respectively, both of which are much lower than those of the diesel generator system, with and without subsidies. The wind power system is also estimated to have a payback period of three years, which is one year shorter than the payback period for the existing diesel generator system.

While the wind power system alone resolves the limitations of the diesel fuel system, further LCOE reduction is desired in order to achieve a rate closer to the current electricity rate of \$0.08/kWh. Three different LCOE least-cost scenarios have been proposed based on LCOE sensitivity and regression analyses, targeting the main LCOE drivers, CRF and CAPEX, in each scenario. It was found that a combination of 40.7% CAPEX reduction and 31.7% CRF reduction produced the smallest LCOE value at \$0.15/kW, as well as an energy subsidy of \$163,941.18 and a payback period of 1.9 years. LCOE least-cost scenario, thus, has successfully reduced the LCOE and subsidy value for wind power system by 35% and 50% respectively.

Although the optimum LCOE value of $0.08/kWh has yet to be reached, this wind power system, with a combination of CRF and CAPEX reduction is technically and economically viable for implementation in the present time and will give benefit to all parties involved in the project. The government could generate power at lower cost and reduce the amount of allocated energy subsidy up to 94% of the current subsidy value. Meanwhile, the foreign investor will profit from the short payback period and lower capital expenditures through tax incentives and an upfront rebate. But, the most benefit would be received by the Eastern Sumba inhabitants, who will finally receive electricity access generated by resources from their own land without being restrained by the availability of the diesel fuel supply.

Future work could address three different things. First is to evaluate other ways to further lower the LCOE value to be equal to the current electricity price of $0.08/kWh. One option is to increase the size of the wind power system, potentially allowing lower LCOE and subsidy rate through the economies of scale. Next, in-depth policy and business strategies could be developed to reduce the CRF and CAPEX value more effectively. More rigorous technical analysis may be conducted to improve wind energy production and to optimize the energy storage use. Finally, further assessment of the wind-hydro hybrid power generation at the Lawola site is plausible, considering the enormous wind and hydro potential power output, while applying economies of scale to lower generation costs and possibly to remove the energy subsidy completely in the Eastern Sumba grid.

Appendix

A. LCOE Model for Monte Carlo Simulation

	Value	Low	High
CAPEX ($)	$3,284,195	$3,119,985.25	$3,448,404.75
OPEX ($)	$229,390	$217,920.50	$240,859.50
CFR	0.0839	$0.08	$0.09
AEPnet (kWh)	2,202,342	$2,092,224.90	$2,312,459.10
LCOE ($/kWh)	**$0.23**	**$0.22**	**$0.24**

Table A.1. LCOE input parameters for Monte Carlo simulation with 5% uncertainties.

B. LCOE LEAST COST SCENARIO STRUCTURES

	Unit Price ($/kW)	Total Price ($)	Price ($/ kWh)	64%
Equipment	$3,235	$2,585,250	$1.17	$1,470.93
Turbine + controller	$2,765	$2,350,250	$1.07	$1,000.93
Storage	$470	$235,000	$0.11	$470
Diesel generator (CAT-32)	$0	$0	$0.00	$0
Balance of System	$15,843	$13,466,550	$6.11	
	$822	$698,945	$0.32	$822
CAPEX	**$3,863.76**	**$3,284,195**	**$1.49**	**$1,949,235.33**

Table B.1. CAPEX reduction calculation for LCOE least-cost scenario

Item	Value	72.59%
Project lifetime (yr)	20	20
Inflation rate (%)	3.18%	0.0318
IRR (%)	11.00%	0.11
Debt (% CAPEX)	80%	0.8
Debt rate	11.60%	3.18%
Tax rate	0.28	7.68%
Depreciation (% CAPEX)	100%	
WACC	**10.86%**	
CFR	0.1245	
inflation-adjusted		
Real return of investment (RROE)	7.58%	7.58%
Real debt rate (RDR)	8.16%	0.00%
WACC	**5.53%**	**1.33%**
CFR	**0.084**	**0.057**

Table B.2. CRF reduction calculation for LCOE least-cost scenario

	LCOE base cost	CAPEX reduction	CRF reduction	Combination
CAPEX ($)	$3,284,194.83	$1,949,235.33	$3,284,194.83	$1,949,235.33
OPEX ($)	$229,390	$229,390	$229,390.10	$229,390
CFR	0.0839	0.0839	0.0573	0.0573
AEPnet (kWh)	2,202,342	$2,202,342	$2,202,341.72	$2,202,341.72
LCOE ($/kWh)	$0.23	$0.18	$0.19	$0.15
LCOE reduction		**22%**	**17%**	**32%**
Subsidy rate	$0.15	$0.10	$0.11	$0.07
subsidy reduction		**34%**	**27%**	**50%**
payback period	2.9	2.2	2.4	1.9

Table B.3. CRF and CAPEX reduction calculation for LCOE least-cost scenario

Glossary

ADB	: Asian Development Bank
AEP	: Annual energy production
BOS	: Balance of System
BPH Migas	: Badan Pengatur Usaha Hilir Minyak dan Gas Bumi (Indonesian Oil & gas Upstream Regulator)
CAES	: Compressed air energy storage
CAPEX	: Capital expenditures
CRF	: Capital recovery factor
DANIDA	: Danish International Development Agency
EIA	: U.S. Energy Information Administration
GDP	: Gross domestic product
IRENA	: International Renewable Energy Agency
IRR	: Internal rate of return
kW	: kilo watt
kWh	: kilo watt-hour
LCOE	: Levelized cost of energy
MW	: Mega watt
NREL	: National Renewable Energy Laboratory
OPEX	: Operational expenditures
PLN	: Perusahaan Listrik Negara (National Utility Company)
SAM	: System Advisor Model

SII	: Sumba Iconic Island
USD	: U.S. Dollar
WACC	: Weighted-average cost of capital
A	: Wind swept area
α	: Wind shear coefficient
Cp	: Turbine capacity
DF	: Debt fraction
EF	: Equity fraction
h	: Hub height
i	: inflation rate
P	: Wind power output
ρ_{air}	: Air density
r_d	: Cost of debt
r_e	: Cost of equity
r_{loan}	: loan rate
ROI	: Return of investment
T	: tax rate
v	: Wind velocity

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Vita

Olivia Loa is a Master of Science candidate in the Energy and Earth Resources at the Jackson School of Geoscience. Born and raised in Indonesia, Olivia is passionate about clean energy technology and economic strategy for fighting energy poverty in rural communities. She was one of the EER Graduate Fellowship recipients and a student scholar for the 2017 International Energy Program Evaluation Conference. Last summer, she had an internship at IC2 Institute, in which she traveled to Poland for gathering information related to economic development through technology commercialization. Prior to joining UT, Olivia received a bachelor degree in Chemical Engineering from University of Wisconsin – Madison. She enjoys traveling, paddle boarding, and food tasting. While not at class, she is volunteering for home-bounded individuals and the Indonesian community in Austin, Texas.

Email: oliviahanjani@gmail.com

This thesis (report) was typed by Olivia Hanjani Loa